Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Barriers and opportunities in the design and delivery of social housing *Passivhaus* for adaptive comfort

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Abstract
This research resides *Passivhaus* concept under the framework of adaptive comfort, reviews two case studies of social housing *Passivhaus* communities in Scotland, and explores the occupants' lived experience and their perception of comfort in *Passivhaus*. The study focuses on the concept of comfort from a socio-technical point of view in order to explore more effective adaptive opportunities that can be integrated at the design stage. Through in-depth interviews with the occupants, site visits and architectural analysis, the research highlights comfort issues in those two social housing *Passivhaus* projects, and identifies barriers and opportunities for behavioural and psychological adaptations specifically for designing social housing *Passivhaus*. The findings suggest that the *Passivhaus* concept has potential opportunities for promoting behavioral and psychological adaptations and sustainable living. However, in order to ensure the energy performance, the design and delivery of *Passivhaus* system in some cases tends to limit the role of occupants and their adaptive opportunities. The research argues that through careful consideration of architectural and mechanical design, and through effective communication of technology and supportive role of community to establish sustainable social norms, the social housing *Passivhaus* can provide the opportunity for the occupants to 'co-evolve' with the house itself, and to achieve a transformation to sustainable living.

Keywords: *Passivhaus* design, adaptive comfort, behavioural and psychological adaptations, social housing, sustainable living

1 Introduction

Passivhaus concept was established in 1990s and has been gradually developed into a rigorous building quality standard over the past twenty years. Regarded as a design methodology that provides comfort with energy efficiency, the standard is widely adopted in Germany and Scandinavian countries. The number of Projects built to *Passivhaus* standard in the UK has also grown rapidly in the past decade. The *Passivhaus* concept sets out performance goals that require the buildings to be designed with a 'fabric first' approach and a hybrid service system, where mechanical ventilation and heat recovery system (MVHR) is often complimented by natural ventilation (Mead et al, 2010). As noted by Nicol (2011), in hybrid buildings, the adaptiveness of indoor comfort depends on the control of hybrid systems. Post occupancy research conducted by Stevenson (2013) suggested that as a new type of hybrid building, *Passivhaus* has employed resilient building envelopes and advanced control systems, which has subsequently raised challenges and barriers for the occupants to adaptive comfort, and maintenance of an established way of living. On the other hand, the *Passivhaus* concept as an environmental statement also embodies the potential to support more sustainable behavioural and psychological adaptations. Distinct from the definition of

Passivhaus concept, the realized *Passivhaus* buildings represent a diverse range of architectural characteristics, and vary in terms of site, construction method and material quality. Since the concept of *Passivhaus* only sets out the performance standard without providing detailed design regulation, the flexibility in approaching the concept enables each project to have its own take in terms of architectural properties such as size, structure system, insulation type, material, orientation, layout, interior fittings, and additional technical devices such as PV panels, wood burner, thermal tank, etc. Construction quality, also varies from project to project. Hence the adaptive opportunities provided by such systems vary between each individual project. Therefore to understand *Passivhaus* concept and design in relation to adaptive comfort, and to study *Passivhaus* buildings on a case by case basis is crucial.

Meanwhile, although much attention has been given to thermal comfort in *Passivhaus* research, other aspects of comfort in relation to the built environment are less explored. This paper argues that the social side of comfort, such as personalized space, ease of housework, etc. is as important for the occupants as physical comfort, especially for social tenants of *Passivhaus*. Those aspects of comfort can affect the occupants' overall comfort evaluation and adaptations, and can also be affected by the adaptive opportunities provided by the built environment. The research presents two case studies of social housing *Passivhaus* projects in Scotland, draws qualitative evidences from occupants interview and architectural analysis, examines the barriers and opportunities for adaptive comfort in the built environment built with *Passivhaus* methodology, in order to improve ways to design *Passivhaus* buildings which use adaptive behaviour to achieve comfort, energy efficiency and sustainable living at the same time.

2 Research context

2.1 Comfort paradigm and adaptation process

The past two decades in the field of thermal comfort research witnesses a paradigm shift from Fanger's seminal (1970) Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) to the adaptive comfort model developed by Humphrey and Nicol (1998). This change has been accompanied and supported by research from sociology and socio-technical study that puts human behaviour at the centre of the attention in thermal comfort, suggesting that users of built environments are active participants rather than passive recipients of comfort, and that comfort is an 'achievement' that needs to be practiced, rather than an 'attribute' (Shove, 2003). The adaptive comfort model recognizes the deviations of what is regarded as 'comfortable indoor environment' in terms of geographical, cultural, socio-economic differences, and emphasizes the relation between inhabitants' comfort temperature and outdoor temperature (Nicol, 2011). It has also been suggested that the indoor comfort can be achieved by three adaptive processes which building occupants undergo in order to 'improve the 'fit' of the indoor climate to their personal or collective requirements' (de Dear et al, 1998). The three adaptive processes are Behavioural adaptation, Physiological adaptation, and Psychological adaptation, among which behavioural and psychological adaptation are the most influential factors for actively acquiring comfort (de Dear et al, 1998).

Behavioural adaptation includes: a) personal adjustment (adjusting clothing, drinking hot beverages); b) technological/environmental adjustment (controlling windows and mechanical equipment); and c) cultural adjustment (changing dress code, rescheduling activities). Psychological adaptation entails the shift of one's expectations regarding indoor climate, which relates more to habituation and experience (de Dear et al, 1998). The evidences of adaptation strategies can be found in a rich selection of literature in thermal comfort research in general, and research on *Passivhaus* in particular. Paciuk (1990) has identified the correlation between 'perceived control', which measures the expectation and perception of control opportunity and comfort satisfaction. Rijal et al (2015) surveyed 120 homes for thermal comfort votes where behavioural adaptation such as the opening of windows and fan use were reported by the occupants to improve thermal comfort. Mlecnik (2013) published a report on *Passivhaus* occupants' satisfaction of comfort which revealed several issues with construction and service/control that have been proven to be common comfort failures in *Passivhaus* construction. Mlecnik's report also showed occupants' adaptation of original settings as response to the problems. Rohdin (2014) also gave a detailed evaluation of how everyday lives were changed by living in *Passivhaus*. For instance, due to large windows on the south side of *Passivhaus*es, behaviour change occurred where occupant either staying away from the windows or used curtains; ventilation habits changed from manually operating windows to using programmable controls (Brunsgaard et al., 2012).

Besides thermal comfort research, Rybczynski (1987) has suggested that from a socio-historical point of view that comfort is highly dependent on social, cultural and historical context. This point of view argued that 'home comfort' is not a static and quantitative figure determined solely by temperature and humidity. The values of the different aspects of comfort appear to differ between individual households, although, also derived and constructed in a collective socio-historical, socio-technical framework (Rybczynski, 1987; Zhao, 2015). Rybczynski (1987) has further painted a picture of how comfort relates to the user of the space. This explains why different appearance and arrangement of rooms (in terms of layout, style, furnishing, services, etc.) made sense during different periods of history, as they contrived 'a setting for a particular type of behaviour'. Another example has been suggested by Canter (1977) that the open fire and hearth have always remained as a focal point in British domestic spaces, and the arrangement of other furniture and activities have been designed around it.

2.2 Delivery of social housing *Passivhaus* system

As noted in an English housing survey (2013), social housing makes up to 17% of all UK homes, and over 10% of the households suffered from fuel poverty. It is particularly relevant to examine social housing that built to *Passivhaus* standard if we wish to improve the energy efficiency and environmental benefits. The first social housing *Passivhaus* in Scotland was completed in 2010. The post occupancy report showed that the appreciation from the occupants regarding the low energy bill and warm indoor environment in the winter, and confirmed the feasibility and benefits of adopting *Passivhaus* system in the social housing sector. More recent research into social housing *Passivhaus* revealed a concern regarding overheating. With the escalation of global warming and the increase of extreme weather such as heatwaves in the near future (Murphy et al, 2010), more and more overheating problems have been noted either by *Passivhaus* occupants or by monitored data in *Passivhaus* research (Masoud et al, 2015; Mlecnik et al, 2012; Ridley et al, 2013).

Social housing *Passivhaus* is especially difficult to design due to the unpredictability of the future tenants. Research conducted by Brown et al. (2015) recommended that designers employ resilient design strategies that allow for varied preferences (e.g., for passive ventilation) to be exercised by inhabitants without undermining suite- or building-level performance. Chui et al (2014) demonstrated the importance of adaptability of social housing by 10 case studies of retrofit project in the UK, and proposed that the relationship between buildings and people can be designed as 'mutually constitutive' and 'co-evolving' through a process of 'interactive adaptation'. Likewise, the social housing *Passivhaus* should fully integrate the adaptive opportunities in post occupancy early on in design stage in order to achieve a state of 'co-evolvement'.

3 Methodology

The variation of the actual delivery of each *Passivhaus* project, as stated before, formed the rationale to study each project on a case by case basis. The case study in this paper includes two sets of data: a) semi-structured interviews, and b) drawings and images of architectural properties and mechanical services. It has been proven to be beneficial to analyse and cross-reference the two sets of data in order to discover comfort and comfort practice in relation to the built environment, and to determine if the design serves as a supportive role for adaptive comfort and provides adaptive opportunities. The analysis of the interview data adopts an inductive process, the open-ended questions are directed by the conversation between the interviewer and the participant, thus the questions asked vary between each household. The questions are organized under three sections. The first section examines the tenants' perception of home comfort, the second section asks about their knowledge and opinions on technology of the house, and the last section explores their lifestyle and behaviour change.

As noted by Goins (2011), textual data often requires a 'reframing of top-down perspectives', for the researcher's assumptions in designing the interview 'may not be shared by the survey respondent' (Goins et al, 2011). The analysis of the interview used text search to pick out keywords of comfort, behavioural and psychological adaptation particularly in relation to architectural properties and mechanical systems in order to examine adaptive comfort from *Passivhaus* design perspective. The analysis focused particularly on discomfort and issues the occupants had when they moved into the new house and how these problems were solved/ adapted to through the lived experience. The architectural properties and mechanical service system are cross-referenced to the interview text to find out what features embedded in *Passivhaus* concept are potential barriers or opportunities for adaptive comfort, and how to successfully overcome the barriers and realize the potentials in designing and delivering the *Passivhaus* system.

4 Two case studies of social housing *Passivhaus* projects in Scotland

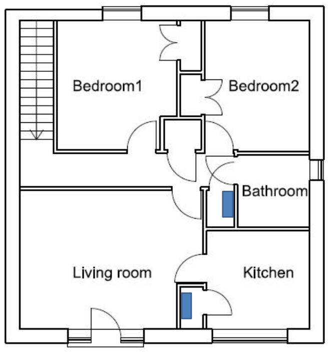
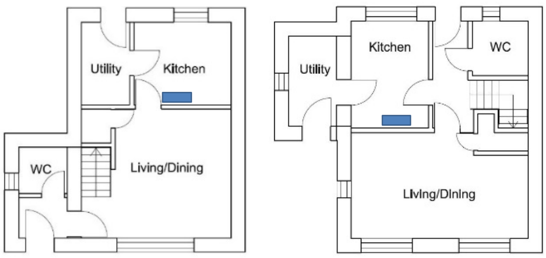
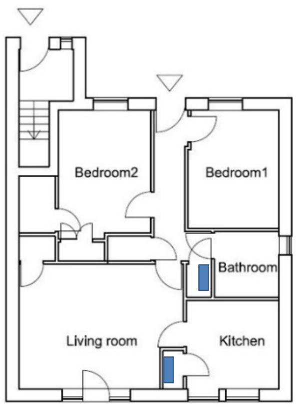
The two studied cases both belong to social housing sector, developed respectively by a private landlord (DO project) and a housing association (SL project). Case DO includes 8 semi-detached houses, four of the households participated in this research (two no. 2 bedroom and two no. 3 bedroom). SL project includes four flats in two semi-detached houses, of which two households took part in this research. The general information can be observed from the following table (Table 1). The two projects have many similarities in terms of floor area, bioclimatic region, construction, household size and service systems, the major difference being the length of occupation – residents in DO project have at least two years of lived experience whereas SL occupants only moved in for less than three months till the date of interview.

Table 1. General information on DO and SL case studies.

	DO project				SL project	
						
Household code	DO1	DO2	DO3	DO4	SL1	SL2
Bioclimatic region	Scotland East					
Construction type	Timber					
Floor area (sq.m)	103	103	88	88	74	80
Household size	3	5	2	2	2	2
Occupants age group	18-60	18-60	18-60	60+	60+	18-60
Occupation date	07/2011				07/2015	
Interview date	05/2014				10/2015	

The DO project is located in the south of Scotland. The two rows of 8 semi-detached timber frame houses are all directly south facing, with limited natural shading on the site. The SL project on the other hand, is facing south-west, and is heavily shaded on the south side of the building. The mechanical system of DO *Passivhaus* features Paul Novus mechanical ventilation and heat recovery (MVHR) unit to provide air circulation, the backup heating is provided by a post heater installed in the MVHR system and a wood burning stove in the living room. The wood burning stove also provides domestic hot water to the household whenever the solar thermal system falls short. All control panels are located in the kitchen or hallway with easy access. The SL project features a similar system, although it is less complex. The MVHR system is more integrated in that it has a built-in thermostat. The domestic hot water is heated by electricity generated from PV panels and stored in a thermal tank. The control panels are located inside cupboards with limited access. The architectural and mechanical properties can be observed in the following table (table 2):

Table 2. Architectural and mechanical properties of DO and SL case studies.

Ventilation strategy	Paul Novus MVHR, opening windows	Genvex MVHR, opening windows
Heating strategy	Post heater on MVHR, wood burner in living room	Post heater on MVHR, electric fire in living room
Water strategy	Solar thermal system and wood burner backed up by immersion heater	PV Panel backed up by immersion heater
Shading strategy	N/A	Natural shading
U Value	Wall: 0.1 W/m^{2}K, Roof: 0.1W/ m^{2}K, Floor: 0.1W/ m^{2}K,	Wall: 0.1 W/m^{2}K Roof: 0.1 W/m^{2}K Floor: 0.1 W/m^{2}K
User interface	 MVHR, thermostat and solar thermal control panel	 MVHR and thermal tank control panel
First floor plan (square indicates MVHR and thermostat control panel location)		
Ground floor plan (square indicates MVHR and thermostat control panel location)		

The demographic information of the interviewees also makes an interesting comparison. The tenants of DO project were initially selected through social housing sector and had no previous knowledge about *Passivhaus*, nor did they move in to the *Passivhaus* specifically for its energy performance feature. Although in the interview there are indications that tenants have increased their knowledge of *Passivhaus*, and showed active change of behaviour through an up to 9 months learning curve. On the other hand, the study on SL project reveals two very distinctive households in terms of their knowledge and confidence in *Passivhaus* system. SL1 occupants knew nothing about *Passivhaus* before moved in and still know nothing about it after three months of occupancy, whereas SL2 occupants, being professionals in home automation technology themselves, had very good knowledge about *Passivhaus* both before and after the occupancy. Yet none of the occupants felt confident in operating the *Passivhaus* or experienced noticeable behavioural or psychological adaptation. The following sections will demonstrate in detail the occupants' opinions on comfort and strategies in adaptations, and will explain their relations to the design of their *Passivhaus*.

4.1 Case DO – 'get into a routine of knowing'

4.1.1 Comfort and built environment

In the interview, all four occupants showed satisfaction when asked about the comfort value of their houses. The DO2 occupant mentioned that the biggest indication of comfort is the change of indoor clothing, specifically in the context of 'having friends' around, so the new house seems to provide a more 'sociable environment' for the tenant as a consequence of thermal comfort. In speaking specifically about thermal comfort, the occupants suggested the house is better at providing shelter from cold weather than at 'getting rid of the heat'. All occupants mentioned the house gets 'a bit too warm' in the summer, especially for DO1 occupant who suggested that mechanical ventilation alone was not sufficient for cooling.

> *DO1: It's comfortable, in the summer it can get warm, really warm, if you don't have your doors and windows open, you can use the ventilation system, MVHR unit, you use that, you know, to cool the house, the ventilation, I don't think that's enough[…]*

In terms of air quality, DO3 occupant suggested the air was a bit dry for her preference, she found it a downside to her health, and opened windows regularly for ventilation. Whereas DO2 occupant considered dry atmosphere as an upside for drying clothes efficiently. The comparison suggested social comfort of convenience outweighs air quality in some cases.

Because of the change in thermal environment and service system, the *Passivhaus* in this project has created issues that need to be adapted to by the occupants. The adaptations are the result of their learning curve, including adjustments to the interior, changes in the occupants' daily activities and habits, and unconscious shift of their concept of comfort and ideology of sustainability.

4.1.2 Behavioural and psychological adaptation

As noted in the previous section, for DO1 occupant, the house gets a bit overheated in the summer, although the thermal environment in winter was quite pleasant. By adjusting the flooring and blinds, the comfort has been tuned to a personal thermal sensation.

> *DO1: Yea, it's really warm [in summer]. My friend J lives across, she got big mats, she's older, she's got curtains, […] Cos I got blinds, everybody else's got curtains, I got blinds. I think it's a lot cooler and airier…*

More interestingly, with a higher indoor temperature and better thermal capacity, the traditional perception and use of a stove as a 'focal point' in the living room has changed. The 'focal point' has slightly shifted away from the stove.

> *DO1: Particularly I think the fire, so before I would put the fire on and it was a nice thing to sit around and I still trying to use the fire like that just to have a nice thing in the room, then I realized it's just completely pointless, cos you just sit there and take off all your clothes and open all the windows […]*

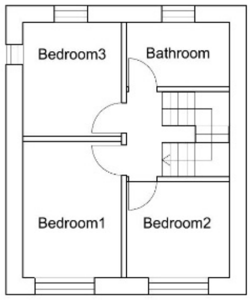
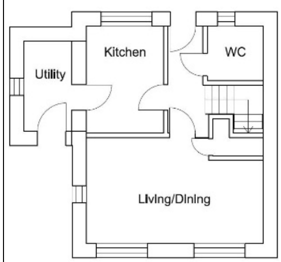
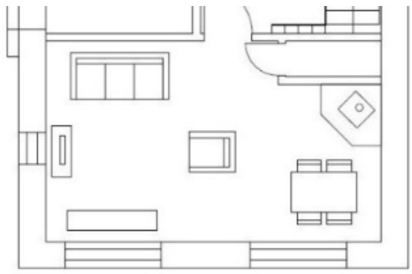
Learning to control the fire is the biggest adaptation for all tenants. Unlike a traditional stove which serves as a heating source, the wood burner in this project performs a different function, as 90% of its heat goes to boil the water. If the stove is to be lit the same way, the tank of water boils very quickly and the system automatically flushes in cold water to prevent overheating. Having tried to resolve the problem for several months in the first winter, the tenants learned then to burn the stove slowly and only light it if necessary. The manager of the estate also installed a simple lighting system by the stove to indicate if it is necessary to light the fire. The occupants showed active changes of behaviour, such as to controlling the stove to specific needs of hot water, and increased awareness of the weather. They have also showed a shift in expectations of indoor environment, and become more patient in waiting for the slow response of temperature change, and achieving internal gains through their lived experience.

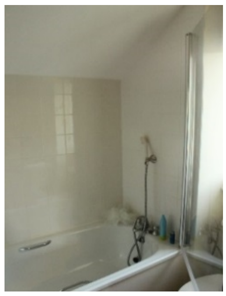
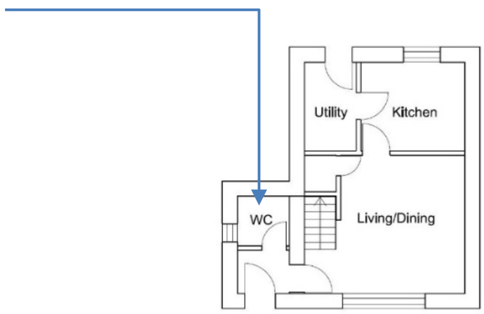
The encouragement given by the housing association has allowed for 'trial and error' to take place, and the technical support has helped the tenants to go through a learning curve. The energy use of each household has been monitored and made available to the tenants, from which the consequences of not using the *Passivhaus* system properly was added to the knowledge base of the community.

> *DO1:[…] the woman who lives down the road who just moved out, she never used the fire, and she never used the solar panels, think she used immersion for hot water, and bills must have been a lot higher, a lot higher.*

When examining those comfort issues and adaptation processes with architectural drawings and photos taken on site, connections can be made between the three. The problems and discomfort experienced by the occupants, the adaptations they made and related architectural and mechanical features of the project are summarized in the table below:

Table 3. Summary of comfort issues, adaptive process in relation to the built environment in DO project

Discomfort /problems	Adaptive process	Built environment
Overheating (in summer)	1. Fitting in curtains/blinds on south-facing windows, and timber floor in living room (House DO1, 3, 4) 2. Open windows to cool the house (House DO2, 3, 4)	 The overheating issue is especially severe in upstairs bedroom2 where the glazing area is relatively large comparing with the room size. The tenants have liberty to arrange interior fittings, the windows are all openable for natural ventilation.
Overheating (from wood burner)	1. Shifting the focal point of living room away from the stove (House DO1, 2) 2. Burn the wood slowly to achieve mild and steady heat (House1, 2, 3, 4)	 The open plan living/dining space enabled the shift of focal point. 
Slow response when trying to increase internal temperature	1. Being patient to wait for the temperature to slowly go up (House DO1) 2. Cook, light up candles or do exercise to use internal gain to increase temperature (House DO1, 2, 4) 3. Thermostat control and thermometer are installed and	 The thermometer installed in every house is indicative.

	accessible to simplify temperature control and visualize actual temperature. (House DO1, 2, 3, 4)	 All control panels are with easy access
Operating wood burner to get DHW	1. Adapting to new ways of operating the wood burner (House DO1, 2, 3, 4) 2. Fitting in a lighting system as indicator to control the stove more efficiently (DO1, 2, 3, 4) 3. Developing the habit of checking the weather frequently (House DO1, 3, 4) 4. Very careful not to use immersion heater (House DO1, 2, 3, 4)	   Immersion heater switch has been tucked away behind shelves intentionally by DO4 occupant so not to use it often.
Shower head too low (reported only by DO4)	The occupant changed the downstairs WC into a shower room.	Flexible layout compensated the design problem and made it possible for the WC to be changed into a shower room.  

4.2 Case SL – 'if we understood this place better we'd be a lot happier'

4.2.1 Comfort and built environment

For both households in SL project, although they did find the flat can 'get a bit hot' during the night, the summer that just passed was quite pleasant, the general opinion on thermal environment is very positive. For SL2 occupants especially, the *Passivhaus* is a big step up in terms of thermal comfort. Other aspects of comfort were also mentioned in the conversation. Privacy is the most praised aspect of comfort. The SL project features a 'reversed plan', where the living room is tucked away from the main road, facing the south-side with a garden view and full bloom of trees, whereas the bedrooms are facing North onto the driveway and car park. From design point of view, it's well suited for *Passivhaus* where the most likely overheated room is naturally sheltered from summer sun, and the bedroom benefits from a slightly colder temperature overall. Although for SL1 occupant, they find the house 'darker' for this very reason, and shared scepticism about the reversed layout. On the other hand, this reversed plan together with the feature of triple glazed windows have been highly praised by SL2 occupants for the privacy the house enables.

> *SL2: This is very good actually, for privacy, if you see back there, trees and hens, you wouldn't need blinds here cuz nobody can see inside, I don't see the neighbours, […] the triple glazing is quite effective. Children next door downstairs, haven't heard a word,[…] I think it's excellent in that sense […]*

Other issues they have encountered in SL1 household includes difficulties to 'keep the house clean', as the doorway connecting living room to the garden doesn't have any steps to stop leaves and insects coming in.

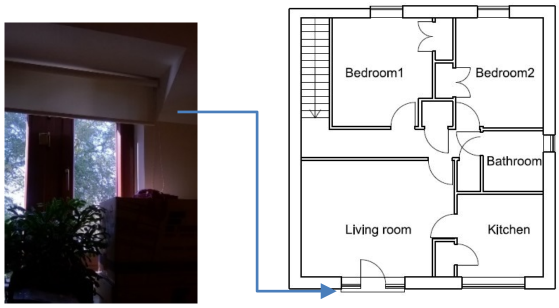
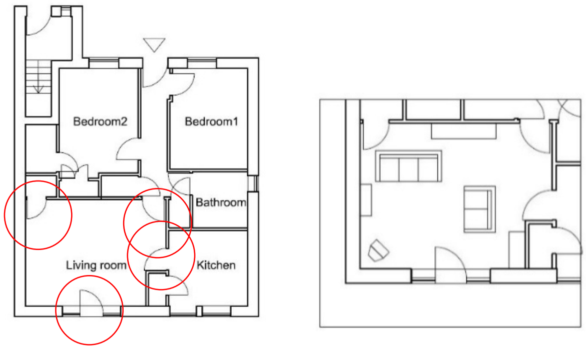
4.2.2 Behavioural and psychological adaptation

Since the SL project has only been completed and occupied in May 2015, the interview captured the first stage of *Passivhaus* living. The first observation was how different the two flats look. According to the occupants, very strict rules applied for alteration and fittings in order not to compromise *Passivhaus* performance. For example, special screws are required, each wall fittings need to be checked so not to penetrate the thermal envelope. As a result, SL2 occupants never had the chance to do any fittings.

Meanwhile, more severe and interesting problem was to do with the technology in their houses. Despite the demographic differences between the two households, they expressed similar opinions and experienced similar changes in their lives. These changes have mainly been adapting to a rural environment, their behaviour and habits in controlling the *Passivhaus* system have yet to be established as a 'routine of knowing'. For both households, the available information regarding the control of the house is far from adequate. There are many mysteries unsolved in controlling the service system. For instance, how to control the temperature, how to get hot water in the winter if the PV panel is covered by snow, what usage does the smart metre actually show, how the PV panel is connected, or what does 'the switch in the cupboard' do? Even though the system has been explored extensively by the SL2 occupants, there are still quite a few uncertainties. Regarding such issues, the conversation with the occupants revealed that the main problem is not what and how much information was given, but the way the information was communicated. A demonstration session was hosted with all tenants just before they first moved in, both occupants suggested they didn't 'take it in'. The tenants were also given a very big user manual afterwards. Both occupants mentioned this 'big booklet' that contains everything they need to know to operate the house, but none of them felt the information was effective. SL2 occupant suggested that the manual was translated directly from German with quite a bit of the instructions lost in translation. Besides communication issue, the interview also revealed that the users were restricted by the housing association from changing the controls on MVHR or thermotank. Once the system was set up and commissioned, the users were told not to change any setting, or to open windows to ventilate. On the other hand, it has also been suggested that the neighbours in this community share knowledge and help each other in adapting to the new environment, although community knowledge sharing was said to be ineffective, the ineffectiveness was due to a collective unknown and a lack of means for collective learning to take place.

Table 3. Summary of comfort issues, adaptive process in relation to the built environment in SL project

Discomfort /problems	Adaptive process	Built environment
Overheating and stuffy (in summer)	Open windows at night to cool the house (House SL1, 2)	The houses are heavily shaded on the south side, which prevents the rooms from overheating. The houses all have openable windows, although the occupants were not recommended to open windows.
SL1 living room too dark	No adaptation observed	Because of the shadings, the occupants felt the living room is very dark. 
Not able to control temperature (default setting not suitable for lifestyle)	Putting a cardigan on, or turn on electric fire when feel cold (House SL1)	The MVHR system in this case has a built-in thermostat in the control panel, but none of the residents knew or understood how to control it. The control panels are located in a dark cupboard that decreased its accessibility 
Not knowing the DHW and PV system	No adaptation observed, occupants are worried about hot water supply in winter when PV system is ineffective	
Not knowing how to use smart metre	No adaptation observed, occupants don't know their energy consumption	The smart metre has been installed in both households, SL1 occupants do not know what it means, SL2 

		occupants are not clear what it measures.
Having trouble to Personalize interior space	For SL2, no major furnishing has been done. The upstairs living room is partially under a tilted ceiling as a result of pitched roof, the door opens inwards, from which the juliete balcony can be accessed. For a lack of means to fit in curtains, blinds have been fitted instead.	
	SL1 occupants furnished the interior despite the housing association suggested otherwise, the living room has four doors opening towards the space which limited the furniture arrangement	
Bath water not hot enough	Using electric shower instead (House SL1, 2)	
No height difference between living room and back yard, hard to clean (House SL1)	No adaptation observed	

5 Discussion: barriers and opportunities in *Passivhaus* design for adaptive comfort

In order to operate the *Passivhaus* to its design intention, adaptations are essential for the occupants. Comparing the two case studies, evidently, the novel technical system of *Passivhaus* has in both cases formed the biggest and most unavoidable barrier in the adaptation process. The temperature, humidity and ventilation control require a new set of knowledge and a certain period of learning process to adapt to. In this process, being able to gain effective information and sufficient support and maintenance from professionals is crucial for adaptation.

Meanwhile, the architectural and mechanical design of the *Passivhaus* also affect how comfort is experienced and achieved through daily lives. In both cases, overheating in summer has been reported as a comfort issue, and the occupants felt the need to open windows to cool the house. The *Passivhaus* standard sets out energy performance goals without specifying any design regulation. This flexibility has been appreciated in DO project where the occupants became an important part of *Passivhaus* system to make adaptations, and to help achieving energy performance, home comfort, as well as sustainable living. Whereas in SL project, the interaction between users and the buildings has been limited to a minimum to ensure a designed performance, as a result the experience of comfort and the opportunity to practise comfort has also been restricted. This has led to dissatisfaction and inactive adaptation. Being able to personalize interior space, to open windows when needed, to perform housework efficiently, and to fully control the indoor thermal environment are important for the occupants to practice comfort and perform active adaptation, in order to achieve an all-encompassing spectrum of comfort.

Furthermore, the potential benefit and opportunity for pro-environmental behaviour in the design of *Passivhaus* community needs to be addressed, particularly in social housing *Passivhaus* where the community plays an important part in promoting sustainable social norms and lifestyle. The DO project has demonstrated how the occupants and their community have evolved together with the *Passivhaus* as they learned to adapt to the house at the same time modified and improved the system. The design of social housing *Passivhaus* has the potential to encourage behavioural and psychological adaptation at a community level to achieve a better-than-best-performance *Passivhaus*-style sustainable living.

6 Conclusion

The *Passivhaus* concept as a quality standard has put a considerable amount of emphasis on energy performance. In order to reach the performance standard, the delivery of *Passivhaus* system adopts resilient design to minimize performance gap. However, the environmental value embodied in *Passivhaus* and other low energy house concepts should be further explored where occupants are the centre of the design for sustainable housing. The design and delivery of such sustainable housing need to focus on the flexibility and personalization of the built environment, and to ensure a good communication and support throughout post occupancy, as well as to establish a collective learning hub for the occupants to fully appreciate sustainable dwellings and its ideology. Rather than seeing occupants as negative factors that compromise the energy performance of *Passivhaus*, the occupant factor should be positively incorporated into design. Occupancy will do much to push the *Passivhaus* idea to a wider domain and realize its full potential for sustainable housing.

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